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# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

JUL 30 1947

TECHNICAL MEMORANDUM

No. 1163

DRAG CORRECTIONS IN HIGH-SPEED WIND TUNNELS

By H. Ludwieg

Translation

“Widerstandskorrektur in Hochgeschwindigkeitskanälen”

Deutsche Luftfahrtforschung, Forschungsbericht Nr. 1955



Washington

July 1947

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DRAG CORRECTIONS IN HIGH-SPEED WIND TUNNELS\*

By H. Ludwig

SUMMARY

In the vicinity of a body in a wind tunnel the displacement effect of the wake, due to the finite dimensions of the stream, produces a pressure gradient which evokes a change of drag. In incompressible flow this change of drag is so small, in general, that one does not have to take it into account in wind-tunnel measurements; however, in compressible flow it becomes considerably larger, so that a correction factor is necessary for measured values. Correction factors for a closed tunnel and an open jet with circular cross sections are calculated and compared with the drag corrections already known for high-speed tunnels.

I. INTRODUCTION

The present report deals with the effect of the finite dimensions of the stream on the drag of models in compressible flow. It will be assumed that the model is in either an infinitely long open jet or an infinitely long closed tunnel in which there is a perfectly constant velocity without the model installation. Therefore, the closed wind tunnel must be slightly tapered to compensate for the effect of the increasing boundary layer. The following tunnel corrections will be applied for these conditions:

- (1) When the model is in an infinitely long air stream the streamlines near the model are diverted and

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\*"Widerstandskorrektur in Hochgeschwindigkeitskanälen,"  
Zentrale für wissenschaftliches Berichtswesen der Luft-  
fahrtforschung des Generalluftzeugmeisters (ZWB) Berlin-  
Adlershof - FB 1955, Göttingen, April 14, 1944.

the velocities increased; however, if the model is in a tunnel of finite dimensions, the streamlines can not bend outward at the walls of the closed tunnel nor the velocity increase at the boundary of an open jet. Instead, an additional flow appears which produces an increase in the velocity of the approaching flow at the model in the case of a closed tunnel and a decrease in the case of an open jet. This correction was extended by B. Göthert (1) and A. v. Baranoff (2) to compressible flow. It is designated below briefly, as the displacement correction factor.

(2) On account of the drag, a region of dead air arises behind the body by which the flow is deflected laterally. Because of the boundary conditions, an additional flow again arises at the boundary of the stream which, while it does not produce a velocity component at the model in the closed tunnel on the other hand evokes an additional velocity at an infinite distance upstream from the model. Since the velocity at an infinite distance upstream from the model serves as a reference quantity, a correction factor is necessary. B. Göthert (1) calculated it for compressible flows and, for short, it is hereafter called the dead-air displacement correction factor. This correction vanishes for free flow.

Aside from these two correction factors, a third one is necessary for the following reason. The additional velocity evoked by the boundaries of the stream on account of the displacement effect of the dead air produces a velocity gradient and, hence, a pressure gradient. Since the model is then in these pressure gradients, it experiences an additional drag or forward-acting force. The correction necessary to compensate for this change of drag will be handled in the present report. It is called the dead-air pressure gradient correction factor.

## II. CALCULATION OF THE CORRECTION FACTOR FOR THE DEAD-AIR PRESSURE GRADIENT WITH INCOMPRESSIBLE FLOW

To begin with, the correction factor is computed for the pressure gradient of the dead air for a closed circular tunnel, and a circular open jet with incompressible flow. Consider a body of revolution located along the axis of

a closed tunnel. As a result of its drag the body has a wake, whose effect on the surrounding air is that of a bar with a drag area  $F_N = \frac{1}{2} c_{wM} F_M$  located behind the body, or a source at the position of the model with the yield (1)

$$Q = \frac{1}{2} c_{wM} F_M v_0 \quad (1)$$

where  $c_{wM}$  is the drag coefficient,  $F_M$  the reference surface, and  $v_0$  the flow velocity of the model. The quantity  $F_N$ , is called the effective wake area, for short.

To define the velocity gradient at the position of a source which is located on the axis of the tunnel and substituted for the dead air, the potential of the source is taken as  $\phi_Q(x, r, \varphi)$  where  $x, r, \varphi$  are cylindrical coordinates and the line  $r = 0$  coincides with the axis of the tunnel. The additional flow, with the potential  $\phi_z$  along the tunnel wall, is defined so that

$$\left( \frac{\partial \phi}{\partial r} \right)_{\text{wall}} = 0$$

for a flow  $\phi = \phi_Q + \phi_z$

the quantity  $\left( \frac{\partial^2 \phi_z}{\partial x^2} \right)_{\text{model}}$  is then the desired velocity gradient at the model.

The calculation of the velocity gradient is reduced to conventional calculations. Multiply the equation  $\phi = \phi_Q + \phi_z$  by the tunnel diameter  $D$  and differentiate with respect to  $x$ .

$$D \frac{\partial \phi}{\partial x} = D \frac{\partial \phi_z}{\partial x} + D \frac{\partial \phi_Q}{\partial x}$$

The expressions appearing in this equation are regarded as the potentials of a stream. Inasmuch as  $\phi_Q$

represents the potential of a source with a yield  $Q$ ,  
 $D \frac{\partial \phi_Q}{\partial x}$  is the potential of a dipole flow of dipole moment,  
 $M_D = Q D$  which is easily confirmed by substitution and  
 differentiation of the source potential. Further,  
 $\frac{\partial}{\partial r} \left( D \frac{\partial \phi}{\partial x} \right) = 0$  along the wall of the tunnel, which  
 follows immediately from the vanishing of  $\frac{\partial \phi}{\partial r}$  along the  
 tunnel wall. Consequently,  $D \frac{\partial \phi_z}{\partial x}$  is the potential of  
 an additional flow which cancels the component of the  
 dipole flow normal to the wall at the tunnel wall. The  
 velocity of this additional flow  $D \frac{\partial^2 \phi_z}{\partial x^2}$  is equal to  
 the desired velocity gradient  $\frac{\partial^2 \phi_z}{\partial x^2}$  except for the  
 factor  $D$ . This additional flow was used, in connection  
 with the displacement correction factor already mentioned,  
 exactly like a dipole, therefore the calculations that  
 have been carried out for this can be applied here.

Let  $p_0$ ,  $\rho_0$ ,  $v_0$ ,  $M_0$ , and  $q_0$  represent the pressure,  
 density, velocity, Mach number, and dynamic pressure in  
 the undisturbed flow far upstream from the model, and  
 $p$ ,  $\rho$ ,  $v$ ,  $M$ , and  $q$  be the corresponding values for the  
 principal flow plus the additional flow. In addition,  
 $p - p_0 = \Delta p$ ;  $\rho - \rho_0 = \Delta \rho$ , etc.

At the dipole, or model, of dipole moment  $M_D = D Q$   
 the additional velocity is:

$$(\Delta v)_{\text{model}} = \tau_v \frac{M_D}{D^3}$$

according to Góthert (1), with  $\tau_v$  a factor depending on  
 the tunnel and the method of suspension in the tunnel.  
 For the example used - a body of revolution in a closed  
 circular tunnel -  $\tau_v = 1.02$ . According to the foregoing  
 $(\Delta v)_{\text{model}}$  is equal to  $D$  times the velocity gradient

of a source  $Q$  at the source. Therefore

$$D \left( \frac{d\Delta v}{dx} \right) = D \left( \frac{dv}{dx} \right)_{\text{model}} = \tau_v \frac{M_D}{D^3}, \text{ because } v = v_0 + \Delta v$$

Substituting  $QD$  for  $M_D$  and the expression from equation (1) for  $Q$  gives

$$\left( \frac{dv}{dx} \right)_{\text{model}} = \frac{\tau_v c_{wM} F_M v_0}{2 D^3}$$

By Bernoulli's theorem

$$\frac{dv}{v_0} = \frac{-1}{2} \frac{dp}{q_0}$$

or

$$\frac{2}{v_0} \frac{dv}{dx} = \frac{-1}{q_0} \frac{dp}{dx}$$

by substitution

$$\frac{2}{v_0} \left( \frac{dv}{dx} \right)_{\text{model}} = - \frac{1}{q_0} \left( \frac{dp}{dx} \right)_{\text{model}} = \frac{\tau_v c_{wM} F_M}{D^3} \quad (2)$$

This is the pressure gradient that the wake behind a body of revolution in a closed tunnel produces at the position of the body.

If a body is in a pressure gradient  $\frac{dp}{dx}$ , it experiences the following additional drag (3):

$$\Delta W = -\alpha \frac{dp}{dx} V_M$$

where  $V_M$  is the volume of the body and  $\alpha = 1 + \frac{V_S}{V_M}$ ,  $V_S$  being the volume of the apparent mass of the body.

Substitution of the value from equation (2) gives

$$\Delta W = \frac{\alpha \tau_v c_{wM} F_M V_M q}{D^3}$$

or

$$\frac{\Delta c_{wM}}{c_{wM}} = \frac{\alpha \tau_v V_M}{D^3} \quad (3)$$

If the model has some type of supports (for example, struts or tension wires) with reference surface  $F_A$  and drag coefficient  $c_{wA}$ , then the appropriate expression for the pressure gradient is:

$$-\frac{1}{q_p} \left( \frac{dp}{dx} \right)_{\text{model}} = \frac{\tau_v c_{wM} F_M + \tau_{vA} c_{wA} F_A}{D^3}$$

For a strut or tension wire running from the axis of the tunnel to the wall, then  $\tau_{vA}$  is approximately 1.15, which can be obtained by extrapolation from G6thert's value for  $\tau_v(1)$ .

For the  $c_w$ -correction factor it follows that:

$$\frac{\Delta c_{wM}}{c_{wM}} = \frac{\alpha \tau_v V_M \left( 1 + \frac{\tau_{vA} c_{wA} F_A}{\tau_v c_{wM} F_M} \right)}{D^3} \quad (4)$$

From equations (3) and (4) it is evident that the correction factor for the dead-air pressure gradient is made considerably larger by high drag at the support.

The derivation for a free stream can be carried out in exactly the same manner. In this case it is only necessary to require that no change of velocity occur at the boundary of the stream. Then exactly the same equation as (4) is obtained, the only difference being in the value for  $\tau_v$  which is  $\tau_v = -0.263$ , for a body of revolution in an open jet.

Therefore, the dead-air pressure gradient in a closed tunnel gives a positive value for  $\Delta c_w$ , that is, an increase in drag. In a free stream it causes a decrease in  $c_w$ . Consequently, the drag values measured in a closed tunnel must be reduced by the correction factor for the dead-air pressure gradient to obtain the values corresponding to the free medium. Conversely, the values measured in the free flow must be increased.

### III. APPLICATION OF THE RESULTS TO COMPRESSIBLE FLOW

#### (a) Definition of the Effective Wake Area

The effective dead-air surface for incompressible flow was:

$$F_N = \frac{1}{2} c_{wM} F_M$$

The corresponding expression for compressible flow will now be defined. According to the momentum theorem, the drag of a body is given by:

$$W = \int_N \rho v (v_0 - v) df$$

when the integration over the wake is carried out in a section behind the body where the static pressure has again reached the value  $p_0$ . Further, it is assumed that this section is located so far behind the body that  $\Delta v = v_0 - v \ll v_0$  and  $\Delta \rho = \rho_0 - \rho \ll \rho_0$ .

Approximately, then

$$W = \rho_0 v_0 \int_N \Delta v df$$

or

$$\frac{1}{2} c_{wM} F_M = \int_N \frac{\Delta v}{v_0} df \quad (5)$$



For the effective dead-air surface  $F_N$ , and, therefore, for the surface over which the flow is deflected by the wake:

$$F_N = \frac{1}{\rho_0 v_0} \int_N (\rho_0 v_0 - \rho v) df$$

or making the same approximations as before

$$F_N = \int_N \frac{\Delta v}{v_0} df + \int_N \frac{\Delta \rho}{\rho_0} df \quad (6)$$

Assuming no heat transfer at the model, it follows from the energy theorem

$$\int_N \left( i_0 + \frac{v_0^2}{2} - i - \frac{v^2}{2} \right) \rho v df = 0$$

where  $i$  represents the heat content. Since  $\rho v df = dm$  is always positive, the expression  $\left( i_0 + \frac{v_0^2}{2} - i - \frac{v^2}{2} \right)$

must vanish across the wake, on the average. As an approximation, it can be set equal to zero for each streamline, which then means that there is a constant stagnation point temperature in the wake. This assumption is also used in the evaluation of loss of momentum measurements (4). Therefore,

$$i_0 + \frac{v_0^2}{2} = i + \frac{v^2}{2}$$

Proceeding from the assumption that  $p = p_0$ , and introducing the quantities  $\Delta v$  and  $\Delta \rho$  while bearing in mind that  $i = \frac{\kappa}{\kappa - 1} \frac{p}{\rho}$

$$\frac{\Delta \rho}{\rho_0} = \frac{\Delta v}{v_0} (\kappa - 1) M_0^2$$

By substitution in equation (6)

$$F_N = \left[ 1 + (\kappa - 1) M_0^2 \right] \int_N \frac{\Delta v}{v_0} df$$

and referring to equation (5)

$$F_N = \frac{1}{2} c_{wM} F_M \left[ 1 + (\kappa - 1) M_o^2 \right] \quad (7)$$

Therefore, the effective wake area  $F_N$  is greater in compressible flow for the same  $c_w$  than the value in incompressible flow by the factor  $\left[ 1 + (\kappa - 1) M_o^2 \right]$ .

This is due to the fact that the wake in compressible flow has a lower density, as well as a lower velocity.

(b) Application of the Formula for the Correction Factor  
for the Dead-Air Pressure Gradient with the  
Aid of the Prandtl Theory

To apply equations (3) and (4) to compressible flow the Prandtl theory will be used in the form of the streamline analogy (5). For the present problem it reads as follows:

Assume a model in flow at a Mach number  $M_o$  in a tunnel of diameter  $D$ ; in a comparison tunnel with diameter  $D \sqrt{1 - M_o^2}$  with a model in incompressible flow whose dimensions including the wake, have been reduced by  $\sqrt{1 - M_o^2}$  at right angles to the direction of flow and remain unaltered in the direction of flow. The additional longitudinal velocities appearing in the compressible flow are then  $\frac{1}{1 - M_o^2}$  times greater than for the corresponding points in the incompressible comparison flow.

However, at corresponding points in the comparison tunnel the additional velocities are  $\frac{1}{\sqrt{1 - M_o^2}}$  times larger on account of the displacement of the dead air

then in the original tunnel with incompressible flow,

since the model is  $\frac{1}{\sqrt{1 - M_o^2}}$  longer in the incompressible

comparison tunnel relative to the diameter, while the cross-sectional dimensions of the model and dead air are equally large relative to the tunnel diameter. Therefore, for the same dead-air displacement in compressible and incompressible flow in the same tunnel, the velocity

gradient increases by the factor  $\frac{1}{(1 - M_o^2)^{3/2}}$ . Besides

since the dead-air displacement for the same values

of  $c_w$  increases by  $\left[1 + (\kappa - 1) M_o^2\right]$  the velocity

gradient increases by  $\frac{1 + (\kappa - 1) M_o^2}{(1 - M_o^2)^{3/2}}$  if the  $c_w$  retains the same value.

Consequently, equation (2) takes the following form for compressible flow.

$$\frac{2}{v} \left( \frac{dv}{dx} \right)_{\text{model}} = \frac{\tau_v c_w M F_M \left[ 1 + (\kappa - 1) M_o^2 \right]}{D^3 (1 - M_o^2)^{3/2}} \quad (8)$$

Bernoulli's equation gives

$$\frac{dp}{q} = - 2 \frac{dv}{v}$$

for compressible flows. It follows from this, that,

$$- \frac{1}{q} \left( \frac{dp}{dx} \right)_{\text{model}} = \frac{\tau_v c_w M F_M \left[ 1 + (\kappa - 1) M_o^2 \right]}{D^3 (1 - M_o^2)^{3/2}}$$

and when we again set

$$W = -\alpha \frac{dp}{dx} v_M$$

there follows

$$\frac{\Delta c_{wM}}{c_{wM}} = \frac{\alpha \tau_v V_M [1 + (\kappa - 1) M_o^2]}{D^3 (1 - M_o^2)^{3/2}} \quad (9)$$

or

$$\frac{\Delta c_{wM}}{c_{wM}} = \frac{\alpha \tau_v V_M \left( 1 + \frac{\tau_{vA} c_{wA} F_A}{\tau_v c_{wM} F_M} \right) [1 + (\kappa - 1) M_o^2]}{D^3 (1 - M_o^2)^{3/2}} \quad (10)$$

Equation (9) holds for a model if the drag effect of the supports is ignored, while this has been taken into account in equation (10). The values to be assigned to the factor  $\alpha$  for compressible flow are discussed in the next section.

#### (c) Bodies in Compressible Flow with a Pressure Gradient

##### (Definition of the Factor $\alpha$ )

It is a well known fact that a body of volume  $V_M$  in an incompressible potential flow with a pressure gradient  $\frac{dp}{dx}$  experiences a drag

$$W = -\alpha \frac{dp}{dx} V_M$$

According to G. I. Taylor (3),  $\alpha = 1 + \frac{V_S}{V_M}$  where  $V_S$

is the volume of the apparent mass of the body. For slender, streamlined bodies  $V_S \ll V_M$ , consequently,  $\alpha$  is approximately equal to 1. The values of the factor  $\alpha$  for compressible subsonic flow with pressure gradients are obtained by application of the energy theorem.

Consider a compressible stream of infinite extent with a pressure gradient in the direction of flow. The pressure, density, velocity, heat content, and internal energy of the undisturbed stream are denoted by  $\bar{p}$ ,  $\bar{\rho}$ ,  $\bar{v}$ ,  $\bar{i}$ , and  $\bar{u}$ , respectively. When a body is in the stream, let  $p$ ,  $\rho$ ,  $v$ ,  $i$ , and  $u$  represent the disturbed values in

the vicinity of the body. Further, assume that there is perfect flow around the body. Then, at greater distances from the body  $p = \bar{p}$ ;  $\rho = \bar{\rho}$ , etc. To continue, the Bernoulli equation

$$1 + \frac{v^2}{2} = \bar{1} + \frac{\bar{v}^2}{2} = \text{Constant}$$

holds for all points in the flow in a reference system fixed in the body. Now imagine a control surface around the body with a large distance between the two, displace the body by an amount  $dx$  with the control surface rigidly fixed and apply the energy theorem to the flow.

The energy removed from the flow by the displacement is then equal to  $W dx$ , where  $W$  is the drag on the body.

$$\iiint_K \rho \left( u + \frac{v^2}{2} \right) dV \text{ is the energy of the gas}$$

enclosed in the control surface, if  $V_K$  is the volume enclosed by the control surface and if  $\rho = 0$  at the positions of the model, in evaluating the integral. The change in the enclosed energy produced by the displacement of the body is then:

$$d \left[ \iiint_{V_K} \rho \left( u + \frac{v^2}{2} \right) dV \right]$$

The increase in energy within the control space due to flow through the control surface during the displacement is

$$\int_{t_1}^{t_2} \iint_{F_K} \rho v_n \left( 1 + \frac{v^2}{2} \right) dF dt$$

when  $t_1$  is an instant prior to the start of the displacement and  $t_2$ , an instant after the displacement at which the stationary state is again reached.  $F_K$  is the control surface and  $v_n$  is the component of the

velocity normal to the control surface. During the displacement of the model the Bernoulli equation does

not apply in the form:  $1 + \frac{v^2}{2} = \bar{1} + \frac{\bar{v}^2}{2} = \text{Constant}$  since the flow in the present reference system (at rest, referred to the original position of the body) is no longer stationary, because of the movement of the model. A closer examination shows, however, that these deviations fall off so rapidly with increasing distance from the model that for very large distances of the control surface from the model, nevertheless, it is possible to write

$1 + \frac{v^2}{2} = \bar{1} + \frac{\bar{v}^2}{2} = \text{Constant}$  and then bring it out in front of the integral. Therefore

$$\int_{t_1}^{t_2} \iint_{F_K} \rho v_n \left( 1 + \frac{v^2}{2} \right) dF dt = \left( \bar{1} + \frac{\bar{v}^2}{2} \right) \int_{t_1}^{t_2} \iint_{F_K} \rho v_n dF dt$$

The integral on the right side simply represents the excess of incoming over outgoing mass between the times  $t_1$  and  $t_2$ . Therefore it follows from the equation of continuity

$$\left( \bar{1} + \frac{\bar{v}^2}{2} \right) \int_{t_1}^{t_2} \iint_{F_K} \rho v_n dF dt = \left( \bar{1} + \frac{\bar{v}^2}{2} \right) d \left( \iiint_{V_K} \rho dV \right)$$

According to the energy theorem the energy of the stream taken up during the displacement must equal the loss of energy of the gas enclosed in the control space plus the excess of energy entering the control surfaces over that leaving. Therefore,

$$W dx = - d \left[ \iiint_{V_K} \rho \left( u + \frac{v^2}{2} \right) dV \right] + \left( \bar{1} + \frac{\bar{v}^2}{2} \right) d \left( \iiint_{V_K} \rho dV \right)$$

Since the undisturbed quantities  $\bar{p}$ ,  $\bar{\rho}$ ,  $\bar{v}$ ,  $\bar{1}$ , and  $\bar{u}$  are not affected by the displacement

$$d \left[ \iiint_{V_K} \bar{\rho} \left( \bar{u} + \frac{\bar{v}^2}{2} \right) dv \right] = 0 \text{ and } d \left( \iiint_{V_K} \bar{\rho} dv \right) = 0$$

where  $\bar{\rho}$ ,  $\bar{u}$ , and  $\bar{v}$  at the positions of the model are assigned the values that prevail when no model is present. From this it follows:

$$W dx = - d \left\{ \iiint_{V_K} \left[ \rho \left( u + \frac{v^2}{2} \right) - \bar{\rho} \left( \bar{u} + \frac{\bar{v}^2}{2} \right) \right] dv \right\} + \left( I + \frac{\bar{v}^2}{2} \right) d \left[ \iiint_{V_K} (\rho - \bar{\rho}) dv \right]$$

The volume integrals which cover the entire volume  $V_K$  enclosed by the control surface are split into two integrals, one of which extends over  $V_M$  the space occupied by the model, while the other extends over the space  $V_K - V_M$  occupied by the fluid while observing immediately that by assumption  $\rho = C$  in the space  $V_M$ . Therefore

$$W dx = d \left[ \iiint_{V_M} \bar{\rho} \left( \bar{u} + \frac{\bar{v}^2}{2} \right) dv \right] - \left( I + \frac{\bar{v}^2}{2} \right) d \left( \iiint_{V_M} \bar{\rho} dv \right) - d \left\{ \iiint_{V_K - V_M} \left[ \rho \left( u + \frac{v^2}{2} \right) - \bar{\rho} \left( \bar{u} + \frac{\bar{v}^2}{2} \right) \right] dv \right\} + \left( I + \frac{\bar{v}^2}{2} \right) d \left[ \iiint_{V_K - V_M} (\rho - \bar{\rho}) dv \right] \quad (11)$$

Essentially, the only contributions to the value of both integrals over  $V_K - V_M$  come from the immediate vicinity of the model since  $\rho \rightarrow \bar{\rho}$ ,  $u \rightarrow \bar{u}$ , and  $v \rightarrow \bar{v}$  at points more distant from the model. Therefore, for sufficiently large values of  $V_K$  the integrals become independent of  $V_K$ .

Assuming only a small pressure gradient in the undisturbed flow, it can then further be assumed as a good approximation that the discrepancies between undisturbed and disturbed flow in the case of flow with a pressure gradient are equal to the discrepancies between the same quantities in a parallel flow with the same Mach number. Now the last two integrals of equation (11) can be evaluated for corresponding parallel flow.

With  $p_0$ ,  $\rho_0$ ,  $v_0$ ,  $i_0$ , and  $u_0$  denoting the undisturbed magnitudes of a parallel flow

$$\begin{aligned}
 & - \iiint_{V_K - V_M} \left[ \rho \left( u + \frac{v^2}{2} \right) - \bar{p} \left( \bar{u} + \frac{\bar{v}^2}{2} \right) \right] dV \\
 & + \left( \bar{i} + \frac{\bar{v}^2}{2} \right) \iiint_{V_K - V_M} (\rho - \bar{p}) dV \\
 & = - \iiint_{V_K - V_M} \left[ \rho \left( u + \frac{v^2}{2} \right) - \rho_0 \left( u_0 + \frac{v_0^2}{2} \right) \right] dV \\
 & + \left( i_0 + \frac{v_0^2}{2} \right) \iiint_{V_K - V_M} (\rho - \rho_0) dV \quad (12)
 \end{aligned}$$

in which the left side is to be evaluated for flow with pressure gradient and the right side for a parallel flow, and  $\rho_0$ ,  $u_0$ ,  $v_0$  must be taken equal to the values of  $\bar{p}$ ,  $\bar{u}$ ,  $\bar{v}$  at the location of the model.

To define the two integrals on the right side one proceeds as follows: On accelerating a model in incompressible flow there is a drag  $W$  where

$$W = \rho V_S \frac{dv}{dt}$$

in which  $\frac{dv}{dt}$  is the acceleration with respect to the fluid and  $V_S$  the volume of the so-called apparent mass.



Correspondingly, for compressible flows

$$W = \rho_0 V_S f(M_0) \frac{dv}{dt} \quad (13)$$

where  $\rho_0$  is the undisturbed density at a distance from the model,  $V_S$  the value of the apparent mass for incompressible flows,  $\frac{dv}{dt}$  the acceleration relative to the fluid and  $f(M_0)$  a function of the Mach number. The magnitude of the function  $f(M_0)$  will be given closer attention later on.

Consider, now that the model is in a parallel flow and moves along with the stream. Then,  $p = p_0$ ,  $\rho = \rho_0$ , etc.

in the entire space occupied by the stream. The flow is viewed from a reference system in which the undisturbed velocity is  $v_0$ . At a great distance from the model there is a perpendicular control surface. Now, let the model be slowed down to rest, gradually and, again, apply the energy theorem to the fluid in the control space.

During the process of slowing down the following energy is taken from the flow

$$\int_{x_1}^{x_2} W dx = \int_{t_1}^{t_2} \rho_0 V_S f\left(\frac{v_r}{a_0}\right) \frac{dv_r}{dt} (v_0 - v_r) dt$$

where  $x_1$ ,  $x_2$ ,  $t_1$ , and  $t_2$  represent the place and time of the beginning and end of the displacement.  $V_r$  is the relative velocity of the model with respect to the undisturbed flow. From this one obtains, then, by

transformation and taking into account that  $\frac{v_r}{a_0} = M$  and  $\frac{v_0}{a_0} = M_0$ :

$$\begin{aligned}
 \int_{x_1}^{x_2} W dx &= \int_0^{v_0} \rho_0 v_S f\left(\frac{v_r}{a_0}\right) (v_0 - v_r) dv_r \\
 &= v_S \rho_0 \frac{v_0^2}{2} \frac{2}{M_0^2} \int_0^{M_0} f(M) (M_0 - M) dM \quad (14)
 \end{aligned}$$

which by setting

$$\frac{2}{M_0^2} \int_0^{M_0} f(M) (M_0 - M) dM = g(M_0) \quad (15)$$

becomes

$$\int_{x_1}^{x_2} W dx = v_S \rho_0 \frac{v_0^2}{2} g(M_0)$$

The change in the energy enclosed in the control space is:

$$\iiint_{V_K - V_M} \left[ \rho \left( u + \frac{v^2}{2} \right) - \rho_0 \left( u_0 + \frac{v_0^2}{2} \right) \right] dv$$

where the integral is taken over the vicinity of the model and  $V_K$  is chosen large enough so that further increases do not affect the integral.

For the excess of energy added over that taken away through the control surface during the braking, one has:

$$\begin{aligned}
 &\iiint_{F_K}^{t_2} \rho v_n \left( 1 + \frac{v^2}{2} \right) dt dF \\
 &= \left( 1_0 + \frac{v_0^2}{2} \right) \iiint_{V_K - V_M} (\rho - \rho_0) dv
 \end{aligned}$$

and here, too,  $1 + \frac{v^2}{2}$  approaches  $1_0 + \frac{v_0^2}{2}$  so rapidly

with increasing separation from the model that one can write this expression in front of the integral for a sufficiently large control surface.

The energy theorem then reads:

$$\begin{aligned} V_S \rho_0 \frac{v_0^2}{2} g(M_0) = & - \iiint_{V_K - V_M} \left[ \rho \left( u + \frac{v^2}{2} \right) - \rho_0 \left( u_0 + \frac{v_0^2}{2} \right) \right] dV \\ & + \left( 1_0 + \frac{v_0^2}{2} \right) \iiint_{V_K - V_M} v (\rho - \rho_0) dV \end{aligned}$$

However, the right side is exactly equal to the right side of equation (12). From this through substitution in equation (11) the following is obtained:

$$\begin{aligned} W dx = & d \left[ \iiint_{V_M} \bar{\rho} \left( \bar{u} + \frac{\bar{v}^2}{2} \right) dV \right] - \left( \bar{I} + \frac{\bar{v}^2}{2} \right) d \left( \iiint_{V_M} \bar{\rho} dV \right) \\ & + d \left[ V_S \bar{\rho} \frac{\bar{v}^2}{2} g(\bar{M}) \right] \end{aligned} \quad (16)$$

Assume now, that the pressure gradient  $\frac{d\bar{p}}{dx}$  is small and constant along the chord of the model, then  $\frac{d\bar{p}}{dx}$ ,

$\frac{d\bar{v}}{dx}$ , etc. must also be considered constant along the model and

$$\begin{aligned} W dx = & \frac{d}{dx} \left[ \bar{\rho} \left( \bar{u} + \frac{\bar{v}^2}{2} \right) \right] V_M dx - \left( \bar{I} + \frac{\bar{v}^2}{2} \right) \frac{d\bar{\rho}}{dx} V_M dx \\ & + \frac{d}{dx} \left[ \bar{\rho} \frac{\bar{v}^2}{2} g(\bar{M}) \right] V_S dx \end{aligned}$$

or taking into account

$$\bar{I} = \bar{U} + \frac{\bar{p}}{\rho} \quad \text{and} \quad \bar{I} + \frac{\bar{v}^2}{2} = \text{Constant}$$

$$W = - \frac{d\bar{p}}{dx} V_M + \frac{d}{dx} \left[ \bar{p} \frac{\bar{v}^2}{2} g(\bar{M}) \right] V_S \quad (17)$$

For adiabatic flow one has

$$\frac{d \left( \bar{p} \frac{\bar{v}^2}{2} \right)}{dx} = - \left( 1 - \frac{\bar{M}^2}{2} \right) \frac{d\bar{p}}{dx}$$

$$\frac{d\bar{M}}{dx} = - \frac{\bar{M}}{2} \left( 1 + \frac{\kappa - 1}{2} \bar{M}^2 \right) \frac{1}{\bar{p} \frac{\bar{v}^2}{2}} \frac{d\bar{p}}{dx}$$

By substituting in (17)

$$W = - \frac{d\bar{p}}{dx} V_M - \left[ \left( 1 - \frac{\bar{M}^2}{2} \right) g(\bar{M}) + \frac{\bar{M}}{2} \left( 1 + \frac{\kappa - 1}{2} \bar{M}^2 \right) g'(\bar{M}) \right] \frac{d\bar{p}}{dx} V_S$$

and, to get a more compact expression, introducing

$$h(\bar{M}) = \left( 1 - \frac{\bar{M}^2}{2} \right) g(\bar{M}) + \frac{\bar{M}}{2} \left( 1 + \frac{\kappa - 1}{2} \bar{M}^2 \right) g'(\bar{M}) \quad (18)$$

then

$$W = - \frac{d\bar{p}}{dx} \left( V_M + h(\bar{M}) V_S \right) \quad (19)$$

which gives

$$\alpha = 1 + \frac{V_S}{V_M} h(\bar{M}) \quad (20)$$

for the factor  $\alpha$  in equations (9) and (10).

Equation (19) now permits the definition of the drag of a model in compressible potential flow with Mach number  $\bar{M}$

and a pressure gradient  $\frac{d\bar{p}}{dx}$ , if the acceleration drag of the same model for the range of Mach numbers between 0 and  $M$ , and, therefore the function  $f(M)$  in equation (13) is known.

For incompressible flow ( $M = 0$ ),  $f(0)$  in equation (13) becomes 1. From that one likewise obtains 1 for the value of  $h(0)$ , and equation (19) goes over to the familiar formula developed by Taylor

$$W = - \frac{d\bar{p}}{dx} (V_M + V_S)$$

The additional drag experienced by a wing which satisfies the assumptions of Prandtl's theory when it is in a flow where a pressure gradient exists will be investigated. The first thing to determine is the value of acceleration drag for such a wing that will give the function  $f(M)$  from which  $h(M)$  can then be obtained.

To begin with, let the wing have a stationary motion with a velocity  $v_0$  in a medium that has the undisturbed values  $p_0$ ,  $\rho_0$ ,  $i_0$ , and  $u_0$  at a distance from the model. In a reference system with axis fixed in the wing the potential  $\phi_S$  of the stationary motion then becomes:

$$\phi_S = v_0 x + \psi_S(x, y, z, M)$$

where  $\psi_S$  approaches zero far from the model. Now if the wing moves with the same velocity and a small acceleration  $b$ , then the velocity field can be considered quasi-stationary. The assumption that the acceleration  $b$  be small is necessary here in compressible flow in contrast to the incompressible flow, since all disturbances must spread out with a finite velocity and since at larger accelerations they produce the larger pressure differences appearing between accelerated and unaccelerated motion, as well as density differences and the corresponding velocity differences. Then the appropriate potential  $\phi$  is:

$$\phi = \left(1 + \frac{bt}{v_0}\right) \left[v_0 x + \psi_S(x, y, z, M)\right]$$

where  $v_0$  is the velocity attained exactly at the time  $t = 0$ . Now to find out how the difference of pressure appearing on the wing surface, at the time  $t = 0$ , between the stationary and accelerated motion depends on the Mach number; for this pressure difference certainly yields the acceleration drag.

For the stationary motion with the assumption of adiabatic flow, Bernoulli's equation reads:

$$i_s + \frac{v_s^2}{2} = i_0 + \frac{v_0^2}{2} \quad (21)$$

Applying the more general form of Bernoulli's equation to the motion that is not stationary:

$$\frac{\partial \phi}{\partial t} + \frac{v^2}{2} + P - U = \text{Constant}$$

The heat content  $i$  can be substituted for the pressure function  $P$  again.  $U$  is the potential of a force field that might be present. Since the reference system fixed in the body is an accelerated reference system, it is necessary to set  $U = bx$ . For the instant  $t = 0$  the general Bernoulli equation then reads

$$bx + \frac{b}{v_0} \phi_s(x, y, z, M) + \frac{\partial \phi_s}{\partial M} \frac{b}{a_0} + \frac{v^2}{2} + i - bx = bx + \frac{v_0^2}{2} + i_0 - bx$$

or

$$\frac{b}{v_0} \phi_s(x, y, z, M) + \frac{\partial \phi_s}{\partial M} \frac{b}{a_0} + \frac{v^2}{2} + i = \frac{v_0^2}{2} + i_0 \quad (22)$$

Since the flow is quasistationary with respect to the velocity field

$$\frac{v_s^2}{2} = \frac{v^2}{2}$$

From this and equation (21) and (22) it follows that:

$$i_g - i = \Delta i = \frac{b}{v_o} \varphi_S(x, y, z, M) + \frac{b}{a_o} \frac{\partial \varphi_S}{\partial M}$$

For adiabatic flow  $\frac{dp}{\rho} = di$  is valid. Since a small acceleration and slender model have been assumed, as an approximation, therefore one can set:

$$\frac{\Delta p}{\rho_o} = \Delta i$$

Then from this it follows that:

$$\Delta p = \rho_o \frac{b}{v_o} \left( \varphi_S + \frac{\partial \varphi_S}{\partial M} M \right)$$

The quantity  $\varphi_S$  is the potential of the increased velocity appearing at the profile. Therefore, according to the Prandtl theory the following holds at the profile surface

$$\begin{aligned} \varphi_S &= \frac{1}{\sqrt{1 - M^2}} \varphi_{S \text{ incompressible}} \\ M \frac{\partial \varphi_S}{\partial M} &= \frac{M^2}{(1 - M^2)^{3/2}} \varphi_{S \text{ incompressible}} \end{aligned}$$

Consequently,  $\Delta p$  becomes, at the profile surface

$$\begin{aligned} \Delta p &= \rho_o \frac{b}{v_o} \varphi_{\text{incompressible}} \left[ \frac{1}{(1 - M^2)^{1/2}} + \frac{M^2}{(1 - M^2)^{3/2}} \right] \\ &= \rho_o \frac{b}{v_o} \varphi_{\text{incompressible}} \frac{1}{(1 - M^2)^{3/2}} \end{aligned}$$

The acceleration drag that appears increases by

$\frac{1}{(1 - M^2)^{3/2}}$ . Therefore, according to equation (13) the

following holds for  $f(M_0)$ :  $f(M) = \frac{1}{(1 - M^2)^{3/2}}$ .

From that and equations (15) and (18) the functions  $g(M)$  and  $h(M)$  also follow

$$g(M) = \frac{2}{M^2} \left[ 1 - (1 - M^2)^{1/2} \right] \quad (23)$$

$$h(M) = \left( 1 - \frac{M^2}{2} \right) g(M) + \frac{M}{2} \left( 1 + \frac{\kappa - 1}{2} M^2 \right) g'(M) \quad (24)$$

The function  $h(M)$  is shown in figure 2. One sees that the factor  $\alpha = 1 + h(M) \frac{V_S}{V_M}$  appearing in equation (9) and (10) is increased further by the effect of compressibility. For slender bodies for which  $\frac{V_S}{V_M}$  is small compared to 1, one can therefore also set  $\alpha = 1$  for compressible flow as an approximation.

The arguments carried out to define the potential drag of a body in compressible flow with a pressure gradient assume that the flow is a perfect potential flow. The validity of the Prandtl theory was only assumed for the definition of the acceleration drag to learn the function  $f(M)$ .

Even after the validity of the Prandtl rule has been exceeded, with the appearance of local supersonic fields, however, the flow can still be considered as loss-free potential flow, if the subsequent passage of the flow into the subsonic region takes place adiabatically and also if, as a coarse approximation, the flow remains loss free in the face of weak shocks (naturally, neglecting the wake due to friction and separation of flow). The increased velocities appearing at the profile circumference are underestimated, in this case, when obtained by Prandtl's theory. Therefore, by the same arguments advanced in the derivation of the function  $h(M)$ , in the application of equations (23) and (24) at Mach numbers exceeding the critical value, the correction factor is somewhat underestimated.

For slender bodies of rotation in incompressible flow  $V_S$  is very small compared to  $V_M$ , so one can



set  $\alpha = 1$  as a good approximation. Now, since the induced velocities increase considerably slower for the body of rotation than for the wing, the function  $h(M)$  deviates from 1 still less, so that one can set  $\alpha = 1$  as a good approximation in compressible flow for bodies of rotation.

#### IV. LIMITATIONS IN THE APPLICATION OF THE CORRECTION FACTOR

So far, the dead air has simply been replaced by a source, at the center of gravity of the model, of such a strength that the displacement it produced downstream from the model was equal to the dead-air displacement. The velocity gradient of the additional flow was then defined at this source on the assumption of constancy over the entire chord of the model. Actually, the substitute source should be split up into many small sources and suitably distributed to fit in along the model and eventually the forward part of the wake. Then the additional flow of all these sources should be determined and from this by integration the velocity gradient which could vary along the model.

To check to what extent the above simplifications are permissible, consider figure 3.

Here the variation of the additional velocity along the tunnel axis is given for a source  $Q$  on the tunnel axis in incompressible flow. According to figure 3 the curve for the closed tunnel is defined for a dipole from the additional flow by integration. The values for the additional flow for a dipole are taken from a calculation by V. Baranoff (2) for the displacement correction factor. Such a single source produces an approximately constant velocity gradient of the additional flow for approximately 0.7 tunnel radius, both upstream and downstream. Therefore, if the model is short (less than 0.7 tunnel radius) it is immaterial how the single sources are distributed inside the model because the resulting velocity gradient is always the same as for a combined source of equal total strength. However, since the principal part of the volume of a longer streamlined body is in the center of the model and, in addition, the

substitute sources are to be applied to the central portion of the body, essentially, the formula derived for incompressible flow can be used up to model lengths of one tunnel diameter.

The variation of the additional velocity for compressible flow for the same breadth of wake is obtained by the Prandtl theorem by increasing the ordinates by a

factor of  $\frac{1}{1 - M_o^2}$  and decreasing the abscissae by a

factor of  $\sqrt{1 - M_o^2}$ .

Therefore, the model length for which calculations can be made with constant velocity gradients is  $\sqrt{1 - M_o^2}$  shorter for compressible flow than for incompressible flow. If the model exceeds the permissible length, the amount by which the correction factor from the derived formula is too large can be estimated from figure 3.

The variation of the additional flow of a source in a free jet with incompressible flow also appears in figure 3. The curve is taken from the work of D. Küchemann and F. Vandry (6). One obtains the variation for compressible flow by the same distortions as for the closed tunnel. It is apparent that the correction factor for the free flow has the opposite sign from the closed tunnel. In addition, the correction factor is only about a fourth as large as for the closed tunnel. The length over which the pressure gradient can be considered constant is likewise smaller for free flow. By means of figure 3 an estimate can be made of the amount by which the correction factor formulas indicate the correction factor too large for longer models.

As stated already, the correction formula for free flow with the same size models in tunnels of the same size is approximately one fourth that for the closed tunnel. With long models, for which the validity of the correction formula has already been exceeded, since it can not be evaluated over the entire length of the model with constant pressure gradients, the effective correction factor with free jet is considerably smaller than a fourth of the correction factor for a closed tunnel.

for the formulas which apply for constant pressure gradients lose their validity with a free jet even with smaller models, and indicate the corrections too large.

## V. COMPARISON OF THE CORRECTION FACTOR DERIVED WITH OTHER DRAG CORRECTION FACTORS AT HIGH MACH NUMBERS

According to Göthert (1) the displacement correction factor furnishes the following values for the dynamic pressure, or  $c_w$ , without taking into account the support:

$$-\frac{\Delta q}{q} = \frac{\Delta c_{wM}}{c_{wM}} = \frac{2\lambda_v \tau_v V_M \left(1 - \frac{M_0^2}{2}\right)}{D^3 (1 - M_0^2)^{3/2}}$$

On comparing these correction factors with the correction factor for the dead-air pressure gradient (equation (9)), it is seen that for incompressible flow ( $M_0 = 0$ ) the correction factor for the dead-air pressure gradient up to the factors  $\alpha$  or  $\lambda_v$ , which are nearly 1 for

slender bodies, is half as large as the displacement correction factor. Moreover, for incompressible flow

$\alpha = 1 + \frac{V_S}{V_M}$  and  $\lambda_v$  is a factor with which the substi-

tute dipole strength can be obtained from the volume of a body and the velocity of flow near it. As Glauert (7) who defines  $\lambda_v$  somewhat differently has shown,  $\alpha = \lambda_v$  exactly for incompressible flow.

The increase of the correction factor with Mach number is different, however, for the two correction factors.

In figure 1 the ratio of compressible to incompressible correction factors for conditions alike in other respects is plotted against Mach number. The correction factor for the dead-air pressure gradient rises considerably faster than the displacement correction factor, so that with  $M \approx 0.35$  the dead-air pressure-gradient correction factor is already just as large as the displacement correction factor, while at  $M = 0$  it was only half as large.

According to Göthert, the dead-air displacement correction factor furnishes for a model without taking into account the support

$$-\frac{\Delta q}{q} = \frac{\Delta c_{wM}}{c_{wM}} = \frac{2 c_{wM} F_M \left(1 - \frac{M_o^2}{2}\right)}{\pi D^2 (1 - M_o^2)}$$

or taking into account the spreading out of the dead air through compressibility and III(a)

$$\frac{\Delta c_{wM}}{c_{wM}} = \frac{2 c_{wM} F_M \left(1 - \frac{M_o^2}{2}\right) \left[1 + (\kappa - 1) M_o^2\right]}{\pi D^2 (1 - M_o^2)}$$

The rise of this correction factor with Mach number is likewise shown in figure 1. It rises even slower with Mach number than the displacement correction factor. Since the dead-air displacement correction factor for incompressible flow and slender bodies with small  $c_w$  is smaller in general than the other two correction factors, it lags behind these even more at higher Mach numbers.

Through the drag of the supports, the dead-air pressure-gradient correction factor can be increased considerably as shown in equation (10). It can then considerably exceed the displacement correction factor if the supports have very large drag for relatively small volume (for example tension wires or struts, on exceeding the critical Mach number).

As an extreme example, consider a streamlined body of rotation with a diameter of 100 millimeters, and a volume 2 liters, in a closed tunnel with a diameter of 1 meter. The body is suspended on six strong 1-millimeter gauge tension wires which run perpendicular to the flow from the model to the wall. The drag coefficient for the model is  $c_w = 0.05$ , for the tension wires it is  $c_w = 1.5$  and the Mach number is 0.8. Then equation (10) gives:

$$\frac{\Delta c_{wM}}{c_{wM}} = 0.13$$

This means that, in this case, the drag is in error by 13 percent because of the dead-air pressure gradients. Displacements correction factor and dead-air displacement correction factor only give 1.3 percent and 0.65 percent, respectively, according to Göthert.

This example shows that attention must be given to this problem in high-speed tunnels in the measurement of models with low drag, to keep the drag of the supports very low so that dead-air pressure gradients will not give false drag indications. Tension wires and, struts too, for which the critical Mach number is reached rather early are, therefore, extremely disadvantageous.

## VI. SUMMARY

It has been shown that in addition to the usual drag and Mach number correction factors for high-speed tunnels which take into account change of velocity at the position of the model due to the model and dead-air displacement, a further drag correction is necessary. This correction factor designated the dead-air pressure-gradient correction factor, is based on the fact that a pressure gradient arises when the dead air departs from the position of the model, which produces an additional drag or forward-acting force. It has been shown that this correction factor is of the same order of magnitude as the other two correction factors and that it can even be considerably larger in special cases. In addition, it rises the fastest of all correction factors with an increase in Mach number under conditions that are otherwise alike.

The following formula has been derived for the dead-air pressure gradient correction in the closed circular tunnel and the circular open jet:

$$\frac{\Delta c_{wM}}{c_{wM}} = \frac{\alpha \tau_v V_M \left( 1 + \frac{\tau_{vA} c_{wA} F_A}{\tau_v c_{wM} F_M} \right) \left[ 1 + (\kappa - 1) M_o^2 \right]}{D^3 (1 - M_o^2)^{3/2}}$$

In this,  $\alpha$  is a factor which depends on the shape of the model and is somewhat larger than 1 for streamlined bodies. For streamlined bodies of rotation  $\alpha = 1$  is

a good approximation. For a wing  $\alpha = 1 + h(M_0) \frac{V_S}{V_M}$  where  $V_S$  is the volume of the apparent mass of the wing in incompressible flow and  $V_M$  the volume of the wing;  $h(M_0)$  is a function of the Mach number which is shown in figure 2.

$\tau_v$  and  $\tau_{vA}$  are factors which depend on the tunnel shape and the installation of the model, that is the mounting in the tunnel. For bodies at the center of the tunnel with small cross extent relative to the tunnel diameter,  $\tau_v = 1.02$  in a closed circular tunnel and  $\tau_v = -0.263$  in a circular open jet under the same conditions.

According to Götthert (4), in the closed tunnel for a wing whose wing span  $B$  is no longer small in comparison with the tunnel diameter  $D$  the factor  $\tau_v$  becomes

B/D	0	0.25	0.5	0.75
$\tau_v$	1.02	1.04	1.06	1.10

By extrapolation to  $B/D = 1$ ,  $\tau_v \approx 1.16$  is obtained for suspension devices (struts and tension wires) reaching from the center of a closed tunnel to the tunnel boundary. The quantity  $V_M$  is the volume of the model and  $c_w$ ,  $c_{wA}$ ,  $F_M$ , and  $F_A$  represent the drag coefficients and, respectively, the reference surfaces of the model (subscript M) and the support (subscript A).

The function  $\frac{1 + (\kappa - 1) M_0^2}{(1 - M_0^2)^{3/2}}$  indicates how many

times larger the dead-air pressure gradient is for a Mach number  $M_0$  than in incompressible flow (compare fig. 1).

In conclusion, in determining drags through loss of momentum measurements, the dead-air pressure-gradient correction factor disappears since the additional drag due to the pressure gradient of the wake is a pure potential drag which is not associated with any loss of flow and, on that account, is not noticeable in the wake.

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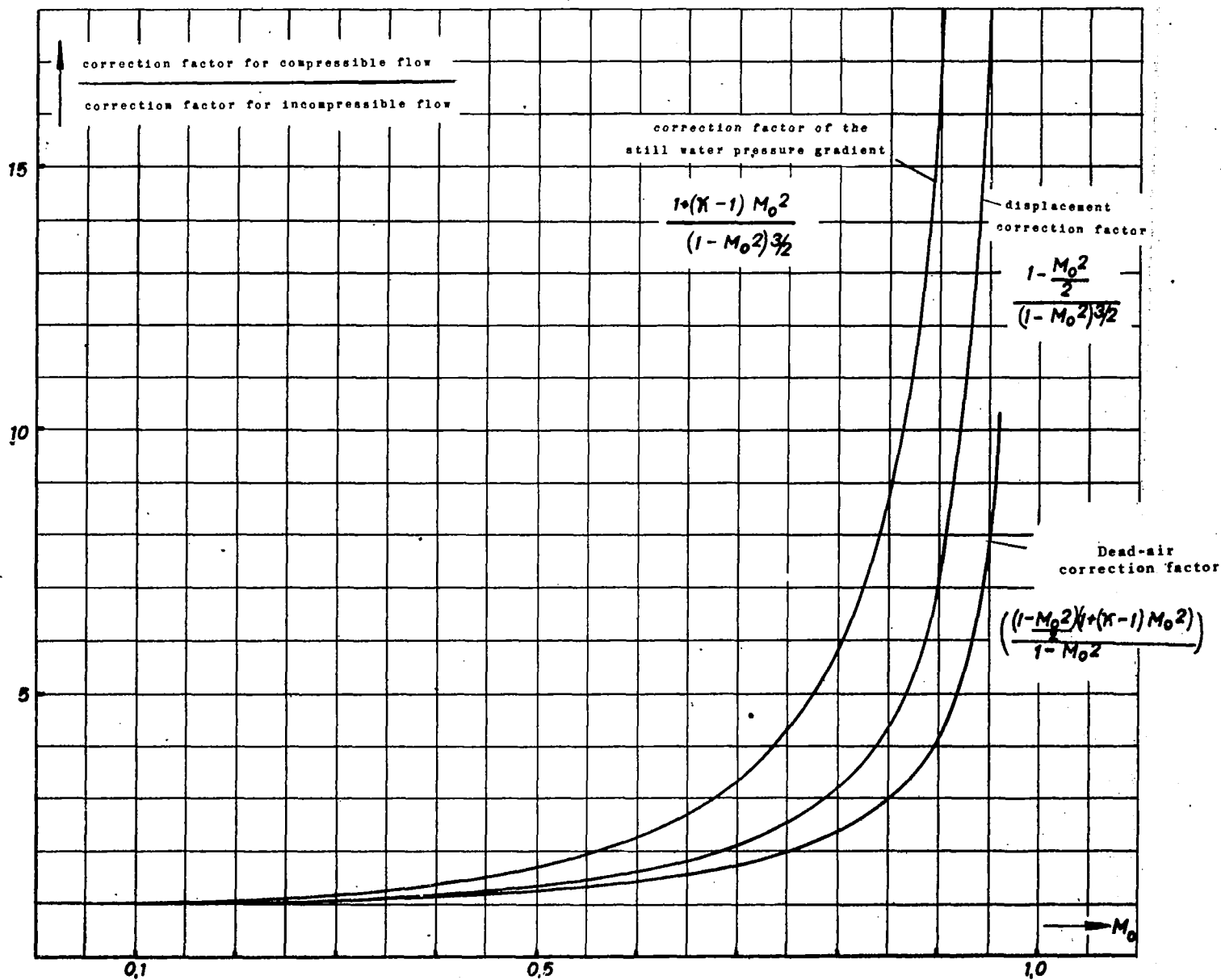


Figure 1. Increase of the correction factors with Mach number.



Fig. 2

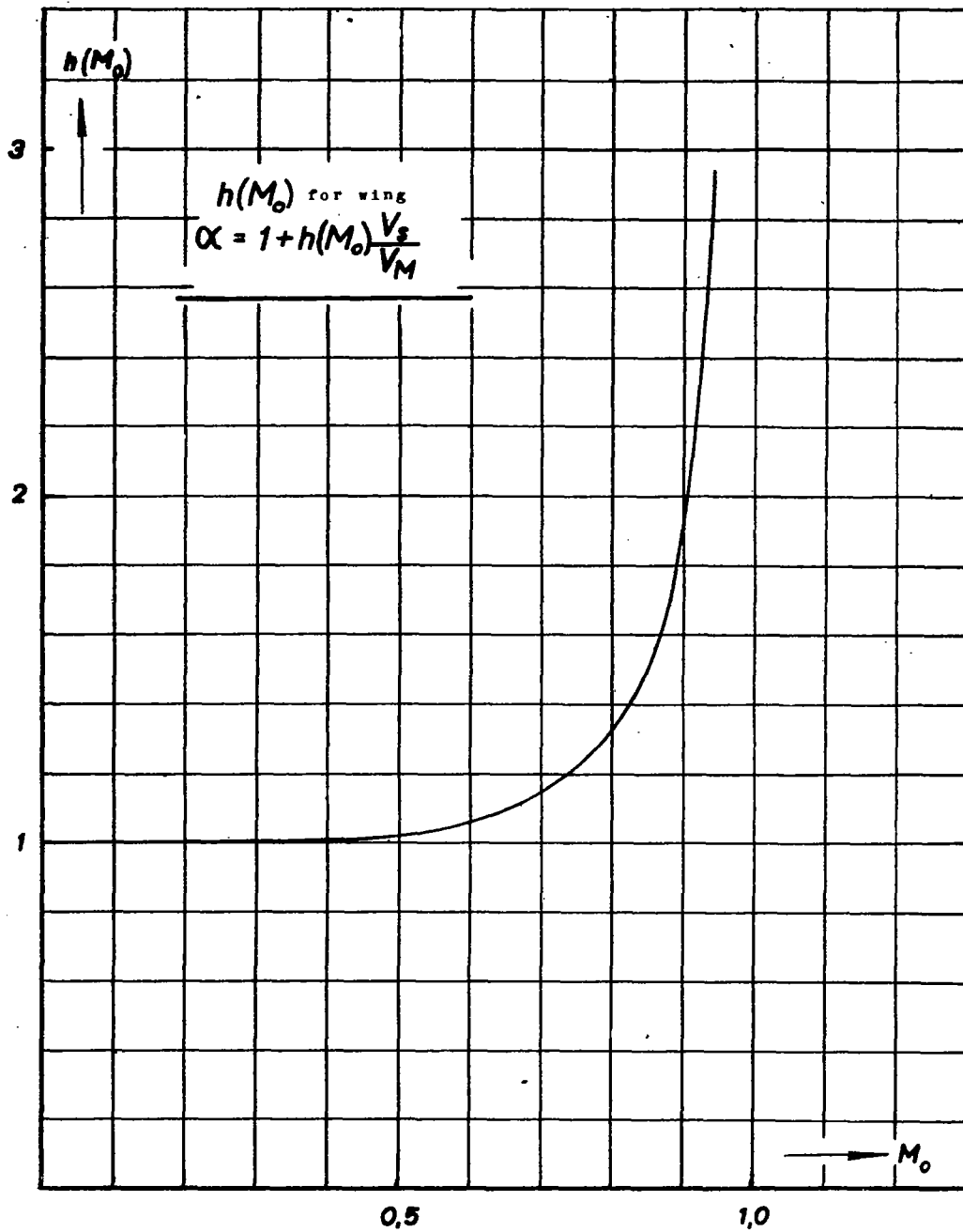


Figure 2.  $h(M_0)$  for a wing.

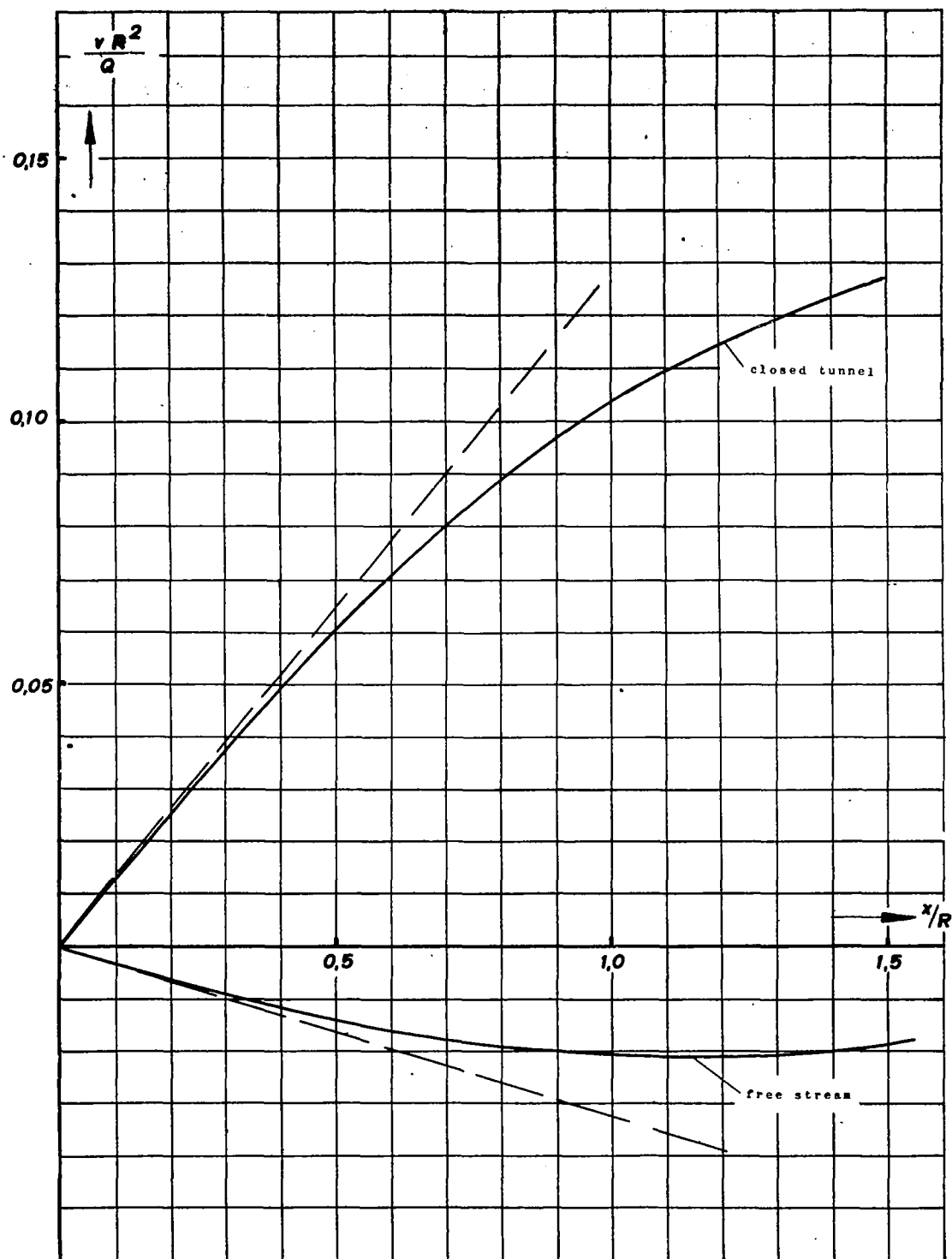


Figure 3. Additional velocity for a source (Q) along the tunnel axis.

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